The Borehole Strainmeter Program in California—Installation and Preliminary Results

*Alan T. Linde, I. Selwyn Sacks, M. Johnston,*F. Wyatt,† and D. Agnew†*

In collaboration with the U.S. Geological Survey and the Institute of Geophysics and Planetary Physics, San Diego, we have initiated a program of installing and recording data from a number of Carnegie borehole volume strainmeters in California. In this program, three separate regions are being instrumented, each to have from three to five strainmeters. Two of the regions, in the Mojave Desert and near San Juan Bautista, were chosen because they are adjacent to sections of the San Andreas Fault which have been associated with large earthquakes and are now of particular interest because of current tectonic activity. The third site, Piñon Flat Observatory, south of Palm Springs, while being in an area of geophysical interest, is unusual in that a number of different types of instruments have been installed for comparative measurements of crustal deformation. So far, only one instrument has been installed at San Juan Bautista. (This will not be discussed further here.) Three have been recording in the Mojave for almost a year, and in April 1982 we installed three at Piñon Flat. The Mojave and San Juan Bautista installations will be expanded to five instruments each as holes are drilled. All the instruments currently installed are in regions of fractured granite.

Piñon Flat Installation

The observatory is located near (15 km) a region (the "Anza gap") which may experience a large earthquake in the near future, and thus the site provides an opportunity to learn about crustal behavior preceding an earthquake. Perhaps more important is the fact that a number of different techniques are being used for monitoring crustal deformation. The measurement of tectonic secular strain has proven to be very difficult. There are few cases where different types of instruments are installed at one site, and there are even fewer examples where instruments show good agreement over periods of months and years. A notable exception has been the net of Carnegie-type borehole instruments installed by the Japan Meteorological Agency in Japan.

At Piñon Flat there are three long-baseline (732-m) laser strainmeters, four long-baseline tiltmeters of different types, borehole tiltmeters, and borehole stressmeters, as well as instruments for precision leveling and for measuring radon in boreholes. In April 1982, we installed at Piñon Flat three Carnegie borehole strainmeters in holes just 300 m apart (Table 9). Thus we will be able to compare our instruments with many others. It is advisable that, at least at one site, such a comparison of instruments be made so that confidence can be assigned to data gathered independently.

The holes were drilled to 800-ft depths in granite and, although only 300 m apart, each showed quite different characteristics. All holes were badly fractured below 700 ft, but otherwise there seemed to be no correlation in fracture locations. Hole CIA had large sections of apparently unfractured rock, CIB was more fractured, and CIC had only a few small sections of unfractured rock. The temperature logs (Fig. 43) show that CIA

TABLE 9. Piñon Flat Borehole Strainmeters

Site	Installation Depth (m)	Date	Location*
CIA	200	21 April 82	33.61 N 116.46 W
CIB	214	4 April 82	
CIC	142	8 April 82	

*Because of the close spacing, the location is the same (to the quoted accuracy) for all three sites.

*United States Geological Survey, Menlo Park, California.

†University of California, San Diego.

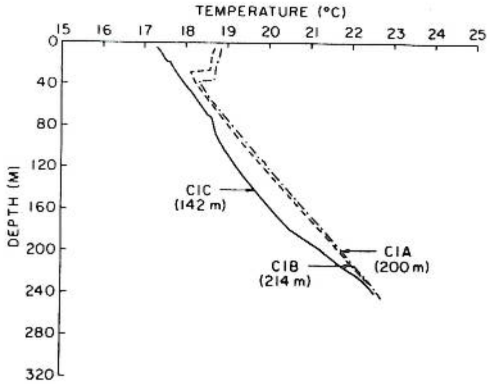

Fig. 43. Temperature vs. depth in the three Piñon Flat holes. Below the water depth (about 40 m), CIA and CIB have uniform temperature gradients. CIC temperature gradient is nonuniform owing to cold water entering at about 70 m and leaving at about 180 m.

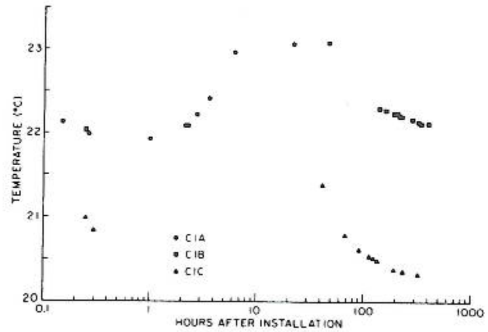

Fig. 44. Temperature vs. time after installation. The initial rapid changes (first 20 hours) are due to the instrument cooling from the surface temperature and then being heated by the grout-curing process. Final temperature for CIC (<20°C) is higher than the preinstallation temperature at that depth (see Fig. 43).

and CIB are well behaved and appear to have no significant water flow, whereas in CIC cold water flows in near the top (~72 m) and out at about 180 m. This cross connection of aquifers can lead to large strain changes which may take years to equilibrate. In the CIC installation, we blocked the hole so as to break the connection between the aquifers.

Recent sensitive temperature measurements by Shimamura and Watanabe (1981) have shown that, at depth, there may be temperature changes (up to 0.1°C) much larger than previously thought possible. Since temperature changes induce strain changes, it is important to monitor the temperature. Thus our instruments now include a thermistor which will allow us to detect temperature changes as small as a few millidegrees. When an instrument is first installed, temperature changes are large due to the instrument being warmed by the Sun prior to descent into the hole and also because the grout-curing process is exothermic (Fig. 44). The variations for CIA and CIB are consistent with these effects and with the initial temperatures in the holes (Fig. 43). The data for CIC are interesting in that the equilibrium temperature is higher than that shown in Fig. 43. The new temperature (>20°C) is approximately that which would obtain if the linear variation of temperature with depth above 70 m were to continue. Thus, in the CIC installation, we sealed off the connection between aquifers and allowed the (presumed) initial temperature gradient to be reestablished.

The instruments are grouted into the hole with expansive cement, and the strain changes for about six months are dominated by the curing of the grout. Normally, instruments are left with the internal valve open during this interval. At Piñon Flat, however, we were on site for some days after the first instruments were installed. Some of the early data are shown in Fig. 45. We were surprised and gratified to see that the instruments were recording high-quality tidal data within a few days of installation.

Mojave Desert

Since June 1981, data have been recorded from three Carnegie borehole strainmeters installed at distances of 3 km, 17 km, and 35 km from the San Andreas Fault near Palmdale. All these instruments are at depths of about 200 m. A summary plot of the data is given in Fig. 46. Tides have been removed for these plots. Calculations for theoretical tides are in very good agreement with

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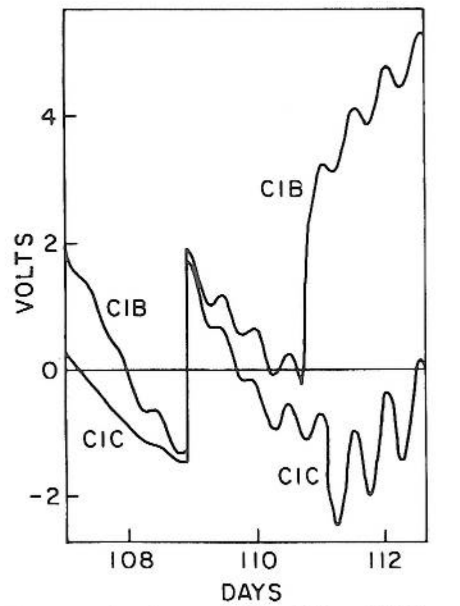

Fig. 45. Strain records from CIB and CIC soon after installation. Rapid jumps are due to opening of valves and gain changes. During these first few days, the grout cures sufficiently to allow measurement of Earth tides. The strain rates are initially negative (dilation) due to cooling. Later strain changes are compressional as the grout expansion becomes dominant.

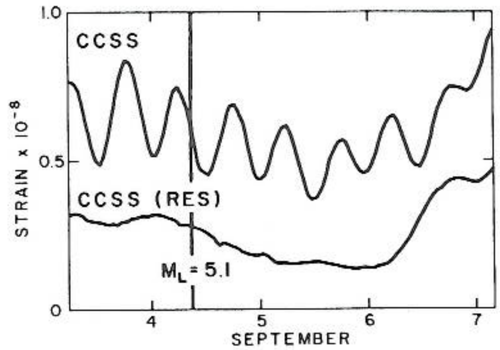

Fig. 47. An example of tidal data on CCSS (upper trace). The lower trace is the result of removing the theoretical tides from the data. The residual record shows no indication of tidal frequencies, indicating excellent agreement between measured and calculated values. On 4 September a local earthquake ($M_L = 5.1$) occurred. The geometry was such that no strain offset should have been observable in the data, and none is apparent.

the recorded data. Figure 47 shows an example of data before and after subtraction of the theoretical tides.

At short periods, all three Mojave instruments record signals (of order 10^{-9} strain) occurring in a semi-regular manner at each station but show no coherence between instruments (Fig. 48). We have made tests to ensure that these signals are not instrument generated; it appears that they are due to local motion on one or more of the many fractures in the rock.

The three instruments do not yet show long-term changes that can be related in any simple manner to the tectonic setting. It is possible that cross connection of aquifers by the drilling has upset the previous environmental equilibrium. We are about to make tests to see if this is a problem. Temperature will be monitored in the holes (these earlier instruments do not incorporate a thermistor), and the holes will be filled with cement to seal off the aquifers.

The instrument CCSS is located within a region monitored by a two-color laser geodimeter. Dilation as measured by the borehole strainmeter and the geodimeter is shown in Fig. 49. (It is interesting to note that despite the proximity of CCSS

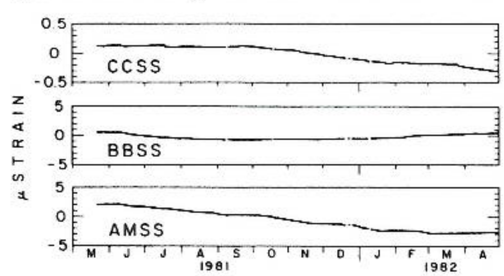

Fig. 46. Strain records from the Mojave instruments. The scale for CCSS is one-tenth that for the others.

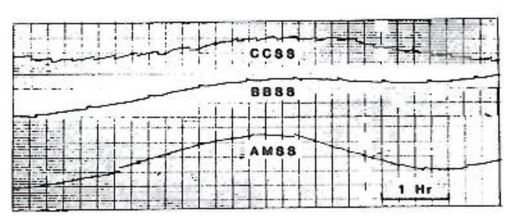

Fig. 48. Short-period data showing noncoherent strain offsets and relaxation (magnitude of order 10^{-9}). The long-period variation is the Earth tide.

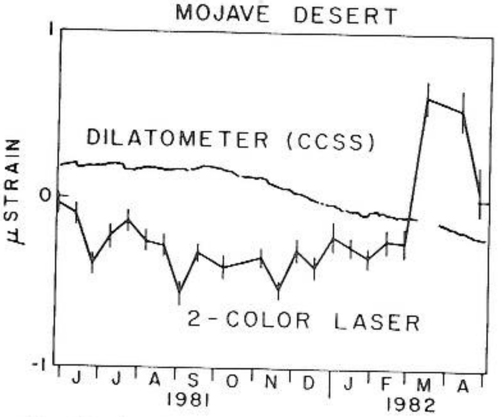

Fig. 49. Strain data from CCSS compared with that from a two-color laser geodimeter. The break in the CCSS record indicates missing data.

to the San Andreas Fault, ~3 km, the strain changes are remarkably small.) While the long-term trends are comparable, it is clear that the geodimeter (which measures the distance between a number of surface locations) records much larger short-period (1–2 months) variations than does the deeper borehole strainmeter. Unfortunately the largest variation in the geodimeter data occurred at a time when strainmeter data was not available owing to a field service problem. However, the strainmeter was operational during the large change measured by the geodimeter in April, but did not record a corresponding variation. While more data are needed to make definitive statements about these differences, our initial interpretation is that the large (several tenths of microstrain) variations the geodimeter detects are related to near-surface effects which are not of importance in considering tectonic deformation. Provided that aquifer-related problems can be avoided or minimized, it appears that the borehole instruments provide a better measure of tectonic strain.

Discussion

In this and the preceding report, we have discussed the implications of some of the strain data from different areas. While we have previously been able to interpret some strain data in terms of tectonic effects (e.g., slow earthquakes, coseismic strain steps), we have concentrated here on what is an ongoing and necessary objective: the understanding of near-surface noise sources and the recording of auxiliary measurements, so that we minimize the possibility of misinterpreting these local noise signals as being tectonically significant.

Reference

Shimamura, H., and H. Watanabe, Coseismic changes in groundwater temperature of the Usu volcanic region, *Nature*, *291*, 137–138, 1981.

FORMATION AND HISTORY OF THE EARTH

Presolar Nebula Formation

Alan Paul Boss

A complete theory of the formation of the solar system must include the sequence of events leading to the formation of the Sun and the accompanying preplanetary nebula. Most of the research on solar system formation to date has assumed the existence of a protosun stabilizing a surrounding nebula, which has some given temperature and density distribution (Safronov, 1969; Kusaka *et al.*, 1970; Weidenschilling, 1980; Coradini *et al.*, 1981; Lin, 1981; Cassen *et al.*, 1981). The details of the formation of the protosun and the structure of the residual nebula should be obtainable from the more general theory of stellar system formation. Numerical calculations indicate that star formation may proceed through a hierarchy of collapse and fragmentation, as suggested by Bodenheimer (1978), with a substantial reduction in the mass and

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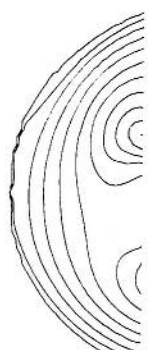

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